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A SNOWFALL PREDICTION METHOD FOR THE ATLANTIC SEABOARD

DAVID B. SPIEGLER

Allied Research Associates, Inc., Concord, Mass.

GEORGE E. FISHER

The Center for the Environment and Man, Hartford, Conn.

ABSTRACT

Melted precipitation and snowfall data from eight winters were used to develop a snow and melted precipitation prediction model associated with 850-mb cyclones along the Atlantic Seaboard. Results indicate that the major potential for heavy snow exists in a band extending from 75 to 225 mi to the left and from 350 to about 1,000 mi ahead of the 850-mb cyclone in the 12-hr period beginning 6 hr after routine upper air observation time. Application of the prediction model of snow amounts to some storms from the 1968–1969 winter season indicate they provide valuable guidance to the forecaster during periods of East Coast storms.

1. INTRODUCTION

The problem of local quantitative snow prediction is recognized by many meteorologists as one of the most difficult of all weather prediction problems. Besides the well-known natural spatial variability of melted precipitation amounts that contributes to quantitative prediction difficulties on a particular day, the spatial variability is even greater for snowfall amounts. This is so because of the sensitivity of the total snowfall to the combined moisture and temperature profile in the lower 3 km of the atmosphere. Despite the inherent difficulties, predictions of snow amounts are routinely provided by the local forecaster during potential and actual snowstorm situations due to public demand for such information.

Numerous investigators have attempted to solve the snow amount prediction problem. Many of them related the sea-level cyclone track and/or the minimum distance of the sea-level cyclone from a particular location to snowfall amounts. Examples of such studies for particular locations are Spar et al. (1967, 1968) for New York City, Penn (1948) for Boston, and Hoover (1960) for Washington, D.C. Two studies that provide general guidance or "rules" for recognizing and forecasting heavy snow are those by Bailey (1958) and Donaldson and Shafer (1965), but their procedures require subjective judgments.

The major goals of this study were to:

1. Develop a simply applied objective prediction procedure for snowfall amounts and melted precipitation amounts associated with 850-mb cyclones along the Atlantic Seaboard.
2. Determine the frequency of significant snow occurrences ($\geq$4 in. in 24 hr) on the synoptic scale along the Atlantic Seaboard without the presence of an 850-mb cyclone (during the period of the sample used).

2. ANALYTICAL PROCEDURES

The cyclone at the 850-mb levels was chosen as the reference cyclone about which the snowfall and precipitation were analyzed. There were several reasons for selecting the 850-mb cyclone rather than the sea-level cyclone:

1. Synoptic experience, and studies by Hanks (1966) and Browne and Younkin (1970) all indicate that heavy snowfalls often occur in bands of varying width, along and mostly to the left of the track of the 850-mb cyclone.
2. The slope between the center of the cyclone at sea level and at 850 mb varies throughout the life history of individual cyclones and also varies from case to case. The slope of the cyclone is related to whether a region is in the cold air both at sea level and at the 850-mb level or only at sea level with "warm" air over the region at 850 mb.
3. Studies by Hilworth (1958), Penn (1957), and others indicate that one of the principal factors in determining precipitation type is the temperature the 850-mb level over the region where precipitation is occurring.
4. The freezing (0°C) isotherm at 850 mb in winter is frequently in the cold air along, or a short distance to the left of, the axis of motion of the 850-mb cyclone.
5. Formation of secondary cyclones at sea level is fairly common along the Atlantic coast, often creating a continuity problem regarding the track of the sea-level circulation while the track of the 850-mb cyclone is normally relatively smooth.

Taken together, these reasons lead to the conclusion that the snow-rain line and the heavy snow band may be inferred more accurately from the projected track of the 850-mb cyclone than from the track of the cyclone at sea level.

A. CASE SELECTION AND DATA

Charts (850 mb) from the period November 1 to April 15 for eight seasons (1960–1961 to 1967–1968) were examined. All identifiable cyclonic circulations in the contour or wind field that appeared in the region shown in figure 1 (areas A and B) were selected. Locations and central height values were recorded. In all, a total of 473 cyclonic circulations (850 mb) and associated storm periods were selected, in which a storm period is defined as the 12-hr period *beginning 6 hr after* normal upper air observation time. There were 170 individual 850-mb cyclones in the sample.

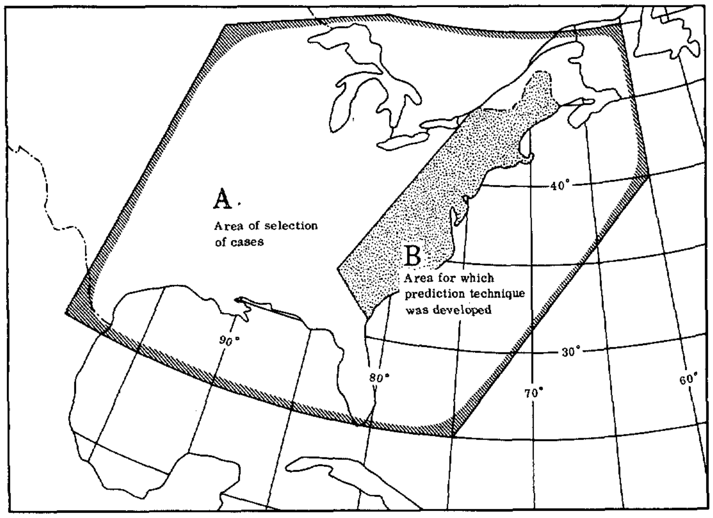


FIGURE 1.—Region for which a snow prediction technique was developed

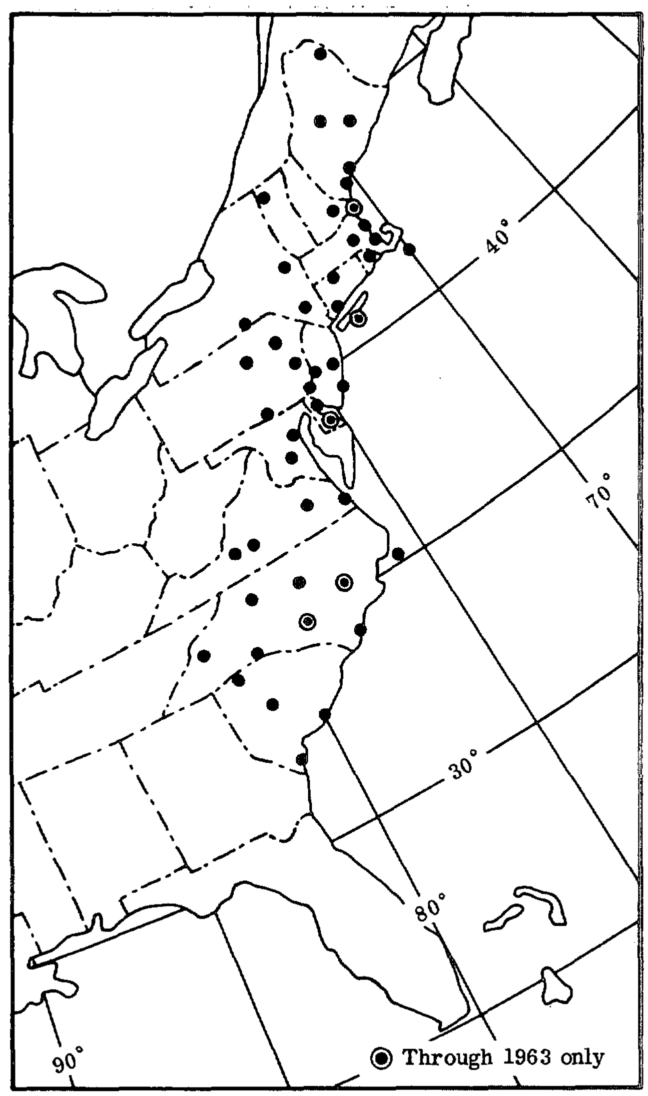


FIGURE 2.—Precipitation stations in the data sample used in the study (1960–1961 to 1967–1968).

Precipitation data corresponding to the eight seasons were supplied by the National Weather Records Center (NWRC, now the National Climatic Center, Asheville, N.C.), for 63 stations within the forecast area (region A of fig. 1). The station locations are shown in figure 2. Six-hour station observations of melted precipitation amount, snowfall amount, snow depth, and precipitation type were provided on a reel of magnetic tape.

B. ANALYSIS PROCEDURE

The data were analyzed around the 850-mb cyclones using an 18°×18° latitude moving coordinate grid (fig. 3) with the origin at the location of the 850-mb cyclone center at initial time (t_0). For each case (storm period), the grid orientation is obtained from the position of the cyclone at initial time and its location 12 hr later (t_{+12}). A computer program transferred the snowfall and melted precipitation data from the station framework to the moving coordinate grid. This was accomplished by computing the relative grid coordinates of a fixed geographical point given a specific grid orientation.[1] For the 473 cases requiring 12-hr precipitation amounts, a total of 22,550, 12-hr station observations were input for these periods. Of these 22,550 observations, 5,400 fell outside the limits of the moving grid and were not used, and 3,870 were missing one or two 6-hr observations and were also eliminated. A total of 13,280, 12-hr observations were used in the final analysis.

The analysis consisted of computations of 12-hr mean snowfall and mean melted precipitation amounts relative to the 850-mb cyclone for each 1° latitude grid square on the moving coordinate grid. For ensuring practical application in an operational environment, the mean snowfall and precipitation amounts were computed for the 12-hr period beginning 6 hr after normal upper air observation time and defined above as a storm period (t_{+6} to t_{+18}). When there was more than one station report within the square for a storm period, the amount allocated to the square for that period was given by the average computed for the stations within the square.

A product of this program is a series of 18°×18° latitude charts summarizing the total data sample. Included are grids of the total number of 12-hr observation periods, the mean melted precipitation, and the mean snowfall, as well as a series of maps showing the percent of 6-hr observations having these types of precipitation:

no precipitation, snow only, rain only,
rain and snow, and freezing rain.

The grids of mean snowfall and mean melted precipitation about the 850-mb cyclone give an *overall* synoptic climatology for all cyclones during the 8-yr data sample.

[1] A FORTRAN IV program (first used in a synoptic climatological precipitation study by Jorgensen 1963) was very helpful in providing guidance for the subroutine used in this study.

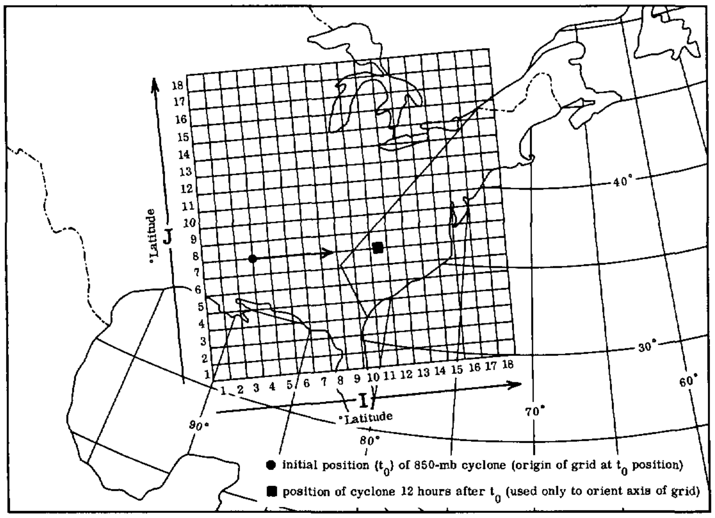


FIGURE 3.—Schematic example of a grid for snowfall distribution about 850-mb cyclones oriented along the projected path of the cyclone.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
18	1	1	1	0	1	0	1	3	2	3	2	6	5	5	3	7	4	3
17	2	1	1	3	0	4	3	4	3	5	4	6	5	8	7	10	8	7
16	1	2	2	7	4	5	2	9	6	3	6	7	8	12	9	8	10	10
15	5	8	4	8	14	10	15	12	14	4	4	13	11	16	14	15	12	14
14	9	10	15	16	16	11	15	18	20	21	19	17	18	29	23	25	21	18
13	15	15	17	26	23	31	29	29	20	26	26	29	30	30	42	28	19	14
12	27	27	27	32	29	34	40	33	44	40	38	39	44	43	40	31	27	20
11	29	30	37	30	38	41	49	46	41	39	54	51	46	46	44	37	30	30
10	40	34	29	48	53	47	48	61	51	53	67	58	52	50	42	43	34	31
9	39	41	44	49	50	55	51	58	58	67	64	52	51	45	38	39	48	33
8	38	31	39	51	55	53	57	57	69	69	56	63	51	43	49	44	51	36
7	33	36	38	46	41	49	57	59	58	58	55	62	67	52	41	44	38	35
6	20	37	37	45	54	38	53	63	57	58	56	55	58	47	53	48	43	26
5	22	26	32	31	50	57	42	60	60	55	58	52	54	50	52	48	38	27
4	20	22	37	25	43	47	35	55	56	59	61	50	48	52	49	44	37	32
3	13	27	26	30	36	42	54	50	60	59	51	56	57	45	36	36	33	22
2	14	25	30	30	36	44	43	42	49	52	47	51	52	50	32	31	29	12
1	10	19	26	28	24	37	32	33	32	39	44	46	39	38	35	21	21	24

Mean azimuth of grid 70.3°

All cyclones regardless of stage of development or location

FIGURE 4.—Number of observed storm periods per grid square.

The field forecaster may be interested in the variation in distributions of snowfall and precipitation due to intensity and stage of development of the cyclone as well as initial location. Thus, the sample of storm periods was stratified by these criteria giving synoptic climatologies of snowfall and melted precipitation which may be used as prognostic fields.

The number of storm periods for which there were observations of precipitation and precipitation types and amounts are shown in figure 4. Although the data sample consists of 473, 12-hr storm periods, the number with observations per grid square is considerably less than that because only limited portions of the grid contain station data for any one storm period. There is, however, a sufficient number of storm periods per grid square (over all but the extreme top portions of the grid) to provide reasonable analyses.

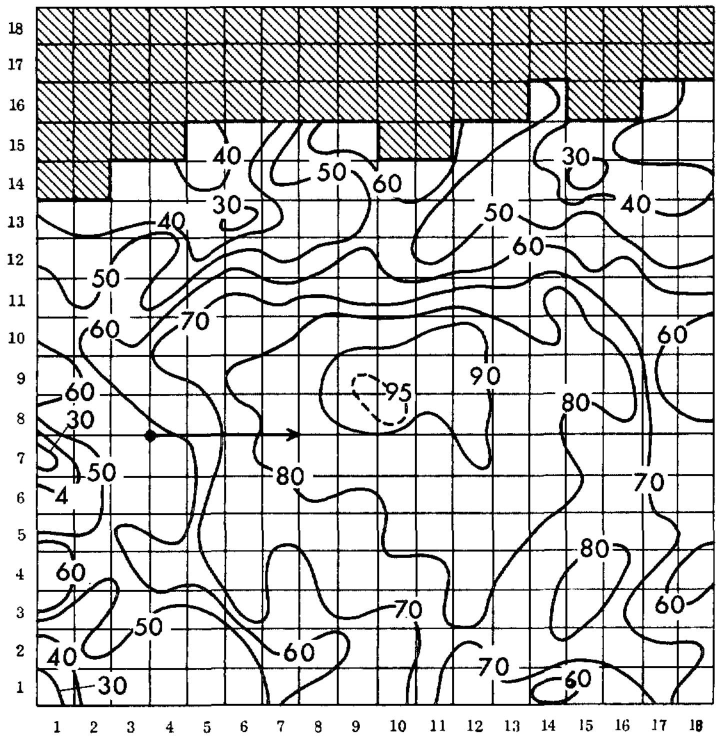
3. RELATIVE FREQUENCY [2] DISTRIBUTION OF PRECIPITATION ABOUT 850-MILLIBAR CYCLONES

A precipitation analysis of the type shown in figure 5 is of value in determining the probability of measurable precipitation, relative to the 850-mb cyclone, in the 12-hr period beginning 6 hr after upper air observation time. The frequency distribution of precipitation illustrated in figure 5 shows a high frequency (≥80%) of precipitation over a large area ahead of the direction of motion of the cyclone (which may be interpreted as high "probability of precipitation"). The probability of precipitation drops off rather sharply in the area about 200 to 350 mi to the left of the direction of motion of the cyclone (i.e., at the top of the figure). This sharp gradient of the frequency of precipitation is not apparent to the right of the axis of motion. The reasons for the high probability of measurable precipitation through this (right-hand) sector are that (1) the moisture values are generally higher in this portion of the cyclone and (2) the frontal surfaces that force mechanical lifting of the air, often resulting in precipitation, normally extend from the cyclone center to the right of its direction of motion.

Figures 6 to 8 show the frequencies of occurrence of various types of precipitation: snow only, rain only, and snow and rain mixed. (These are *not* conditional frequencies; these and the precipitation cases are actual observed frequencies of occurrence.) Figure 6 shows a fairly high frequency (≥60% probability) of "snow only" in a narrow band approximately 75 to 200 mi to the left of the direction of motion, with the strongest *gradient* of "snow only" between 75 mi to the left and 50 mi to the right of the direction of motion. This information, combined with that in figure 8 (frequencies of mixed snow and rain), may be interpreted as indicating that the *snow-rain line is most often located 50 to 75 mi either side of the direction of motion of the 850-mb cyclone.* Thus, the track of the 850-mb cyclone contains predictive information relative to the type of precipitation that will occur over a given area.

All of the above information is physically consistent with the structure and circulation fields of the "average"

[2] The term "relative frequency" is used because the percent frequency is based on differing numbers of cases for each grid square. Where frequency is used throughout the discussion, it always refers to relative frequency.

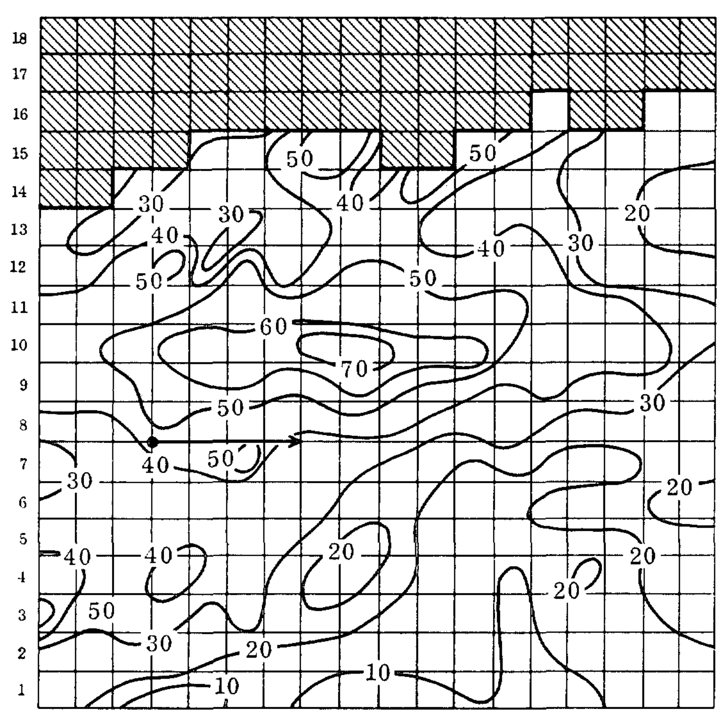


<10 storm periods per grid square

850-mb cyclone center t_0 and direction of motion (t_0 to t_{+12})

All cyclones regardless of stage of development or location

FIGURE 5.—Percent of the 6-hr observations having precipitation.

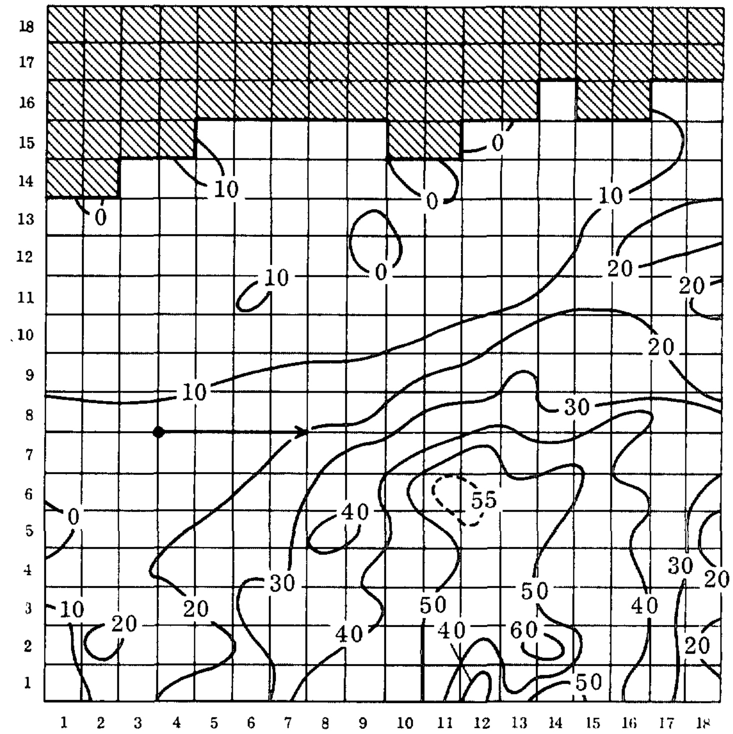


<10 storm periods per grid square

850-mb cyclone center t_0 and direction of motion (t_0 to t_{+12})

All cyclones regardless of stage of development or location

FIGURE 6.—Percent of the 6-hr observations having snow only.

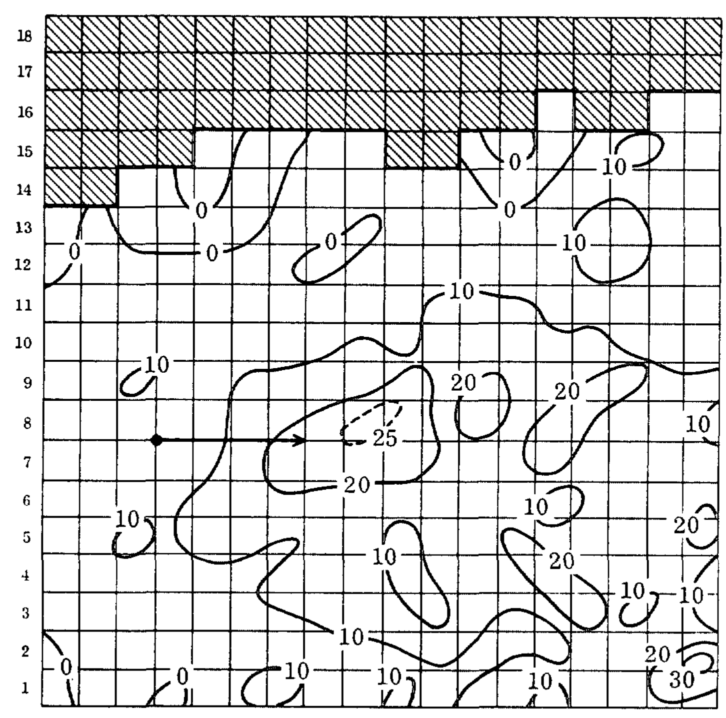


<10 storm periods per grid square

850-mb cyclone center t_0 and direction of motion (t_0 to t_{+12})

All cyclones regardless of stage of development or location

FIGURE 7.—Percent of the 6-hr observations having rain only.



<10 storm periods per grid square

850-mb cyclone center t_0 and direction of motion (t_0 to t_{+12})

All cyclones regardless of stage of development or location

FIGURE 8.—Percent of the 6-hr observations having mixed rain and snow.

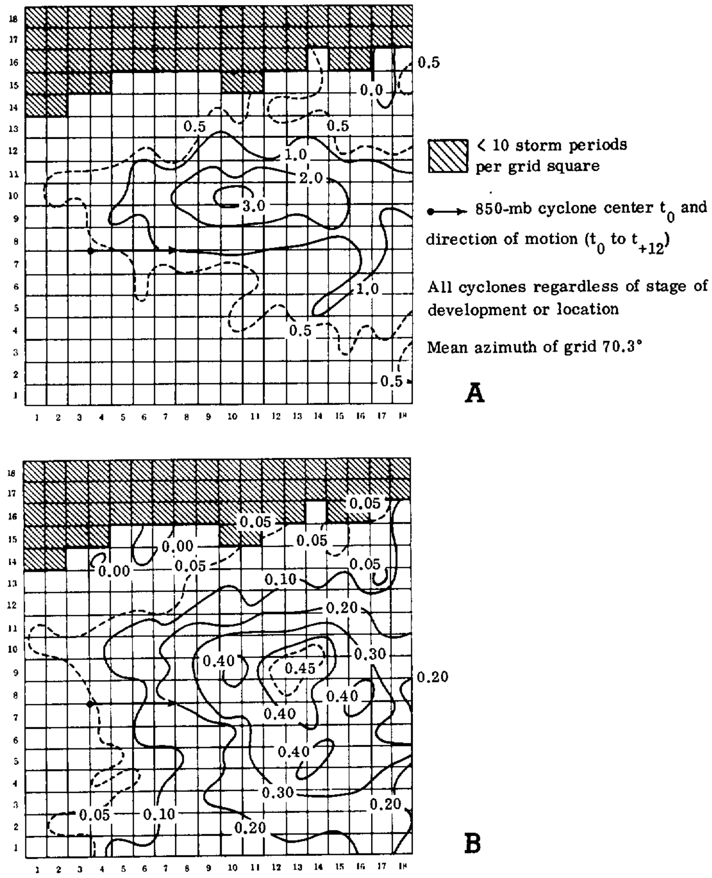


FIGURE 9.—(A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

850-mb cyclone; that is, cold air is usually present to the left and warmer air to the right of the track of the 850-mb cyclone. Areas to the left of the track do not normally experience significant warming; areas along the axis are usually a transition zone between cold and warm air and experience snow or rain.

4. TWELVE-HOUR MEAN SNOWFALL AND MELTED PRECIPITATION AMOUNTS ABOUT 850-MILLIBAR CYCLONES

A. AVERAGE CYCLONES AND STRATIFICATION BY INTENSITY AND STAGE OF DEVELOPMENT

As mentioned earlier, the snowfall and precipitation amounts are for the 12-hr period beginning 6 hr after routine upper air observation times, which makes them useful in a prognostic sense in appropriate situations. Application of those fields in an operational environment is discussed in section 5.

Figures 9A and 9B show the mean snowfall and mean melted precipitation for all cyclones, regardless of stage of development. The noteworthy information in these figures is that (1) there is a large area of significant amounts of mean melted precipitation ($\geq$0.3 in.) extending from approximately 300 to 1,000 mi ahead of, and from 225 mi to the left and 300 mi to the right of, the cyclone track and (2) the area of *mean* snowfall maximum ($\geq$2 in.) extends from about 300 to 850 mi ahead of, and from 75 to 250 mi *to the left, only*, of the direction of motion of the cyclone.

TABLE 1.—*The 850-mb categorization system*

Intensity and stage of development	Average wind speed* over 500-mi radius of cyclone center (kt)
Weak open wave	10–30
Moderate open wave	30–45
Strong open wave	>45
Weak occlusion	10–30
Moderate occlusion	30–45
Strong occlusion	>45

*To determine the average wind speed within a 500-mi radius of the cyclone center (necessary to the specification of the appropriate intensity of the cyclone), we divided the cyclone into four equal quadrants. If there were three or more upper air wind observations within each quadrant, we averaged those for each quadrant and then computed a mean of the four averages. For those quadrants where upper air wind observations are not available, we determined the average wind speed geostrophically, using a geostrophic wind scale at three equally spaced points out to 500 mi from the cyclone center. For quadrants with one or two upper air wind observations, we obtained the necessary number of geostrophic wind speeds to equal at least three "observations."

For determining how the distributions of snow amount and melted precipitation amount vary from the averages given by all cyclones, the cyclones were stratified by intensity and stage of development according to the criteria listed in table 1.

Results for these categories and combinations of categories are shown in figures 10 to 15. Each stratification naturally consisted of less than the total number of storm periods; the grid squares in which there were less than 10 or less than five storm periods with data are indicated by annotations on the figures. For three categories, strong open waves, weak occlusions, and strong occlusions, the number of storm periods was insufficient to analyze the data. Significant results are the following:

1. Precipitation amounts (mean melted precipitation and mean snowfall) are considerably higher (maximum amounts approximately twice as great) for the moderate and strong cyclones than for weak cyclones. These results are in agreement with those reported by Klein et al. (1968) in a study of relationships between upper air Lows and winter precipitation in the Western Plateau States. They found heaviest precipitation associated with the more intense cyclones.
2. The significant snowfall area (mean snowfall >2 in.) is located almost entirely to the left of the cyclone track in a band from 75 to 225 mi to the left of and from 350 to as much as 1,100 mi ahead of the cyclone.
3. Significant snowfalls to the right of the cyclone track are observed for moderate occlusions in which warm air flow is cut off at the 850-mb level by the occlusion process.
4. Mean grid azimuths (deg. from north) indicate a more northerly component for moderate open waves than for weak open waves (59.5° moderate, 75.4° weak open waves). The combination of categories "moderate" and "strong" open waves (not shown) had a grid azimuth of 57.3°.
5. Mean grid azimuths for moderate occlusions show less of the northerly component than for moderate open-wave cyclones (70.2° moderate occlusion, 59.5° moderate open wave).

Because frontal analysis is not included in the present 850-mb charts that are transmitted over facsimile by the National Meteorological Center (NMC) at Suitland, Md., figures 13 to 15 show combinations of categories based solely on intensity (e.g., weak open waves and weak occlusions).

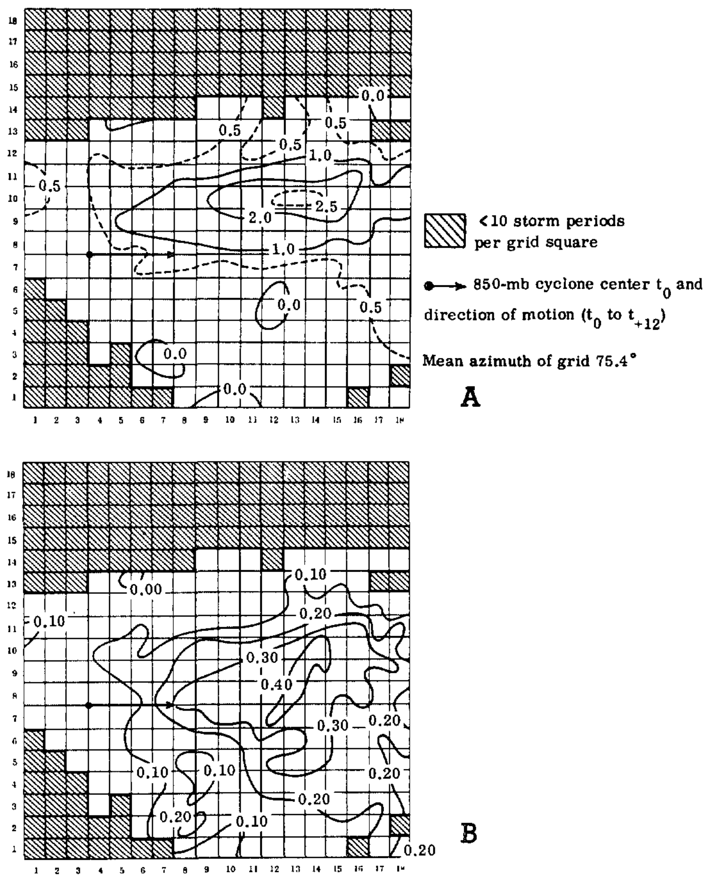


FIGURE 10.—Weak open waves, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

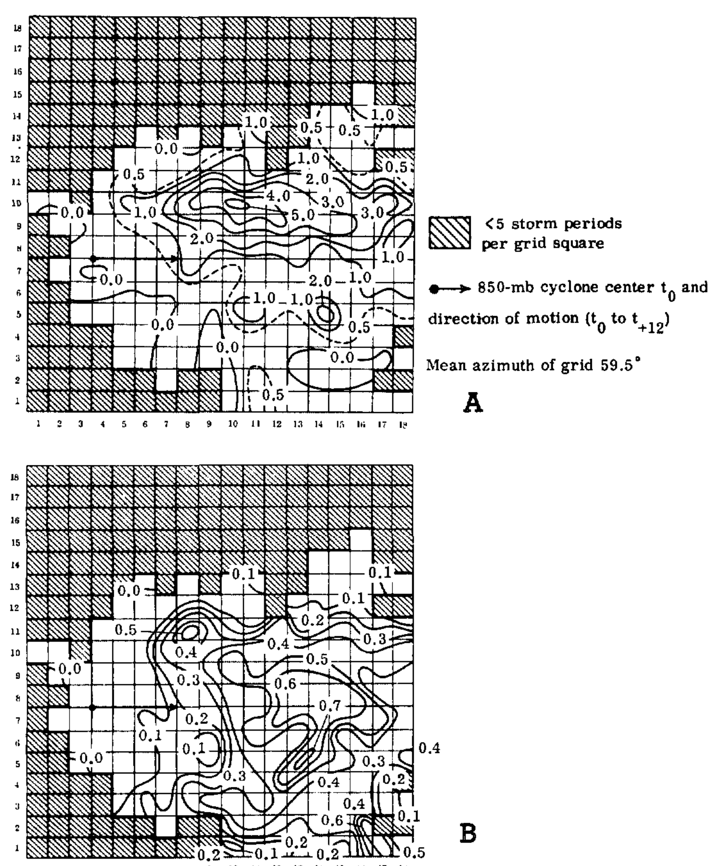


FIGURE 11.—Moderate open waves, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

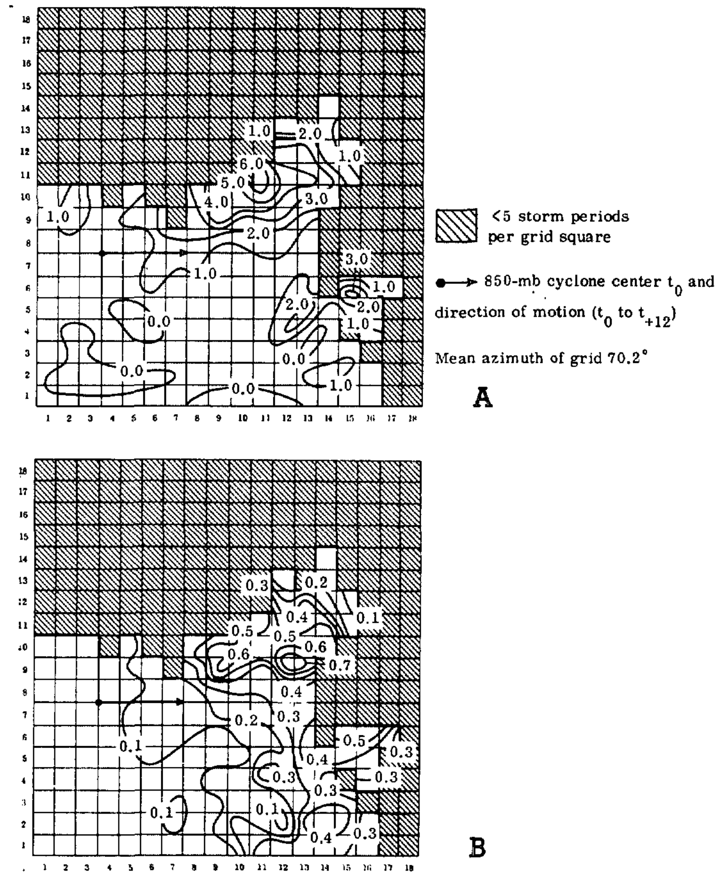


FIGURE 12.—Moderate occlusions, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

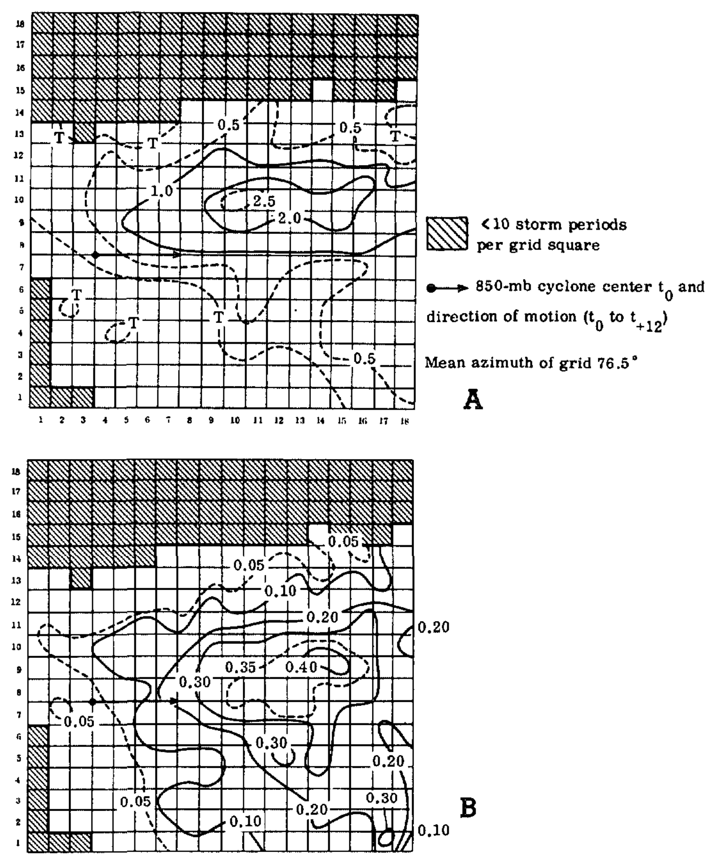


FIGURE 13.—Weak open waves and weak occlusions, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

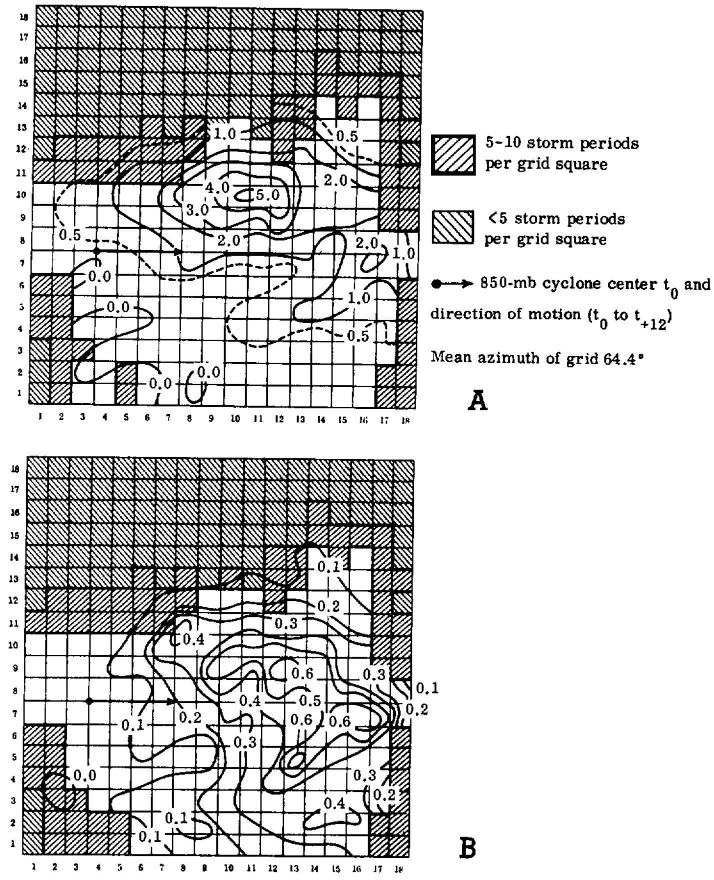


FIGURE 14.—Moderate open waves and moderate occlusions, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

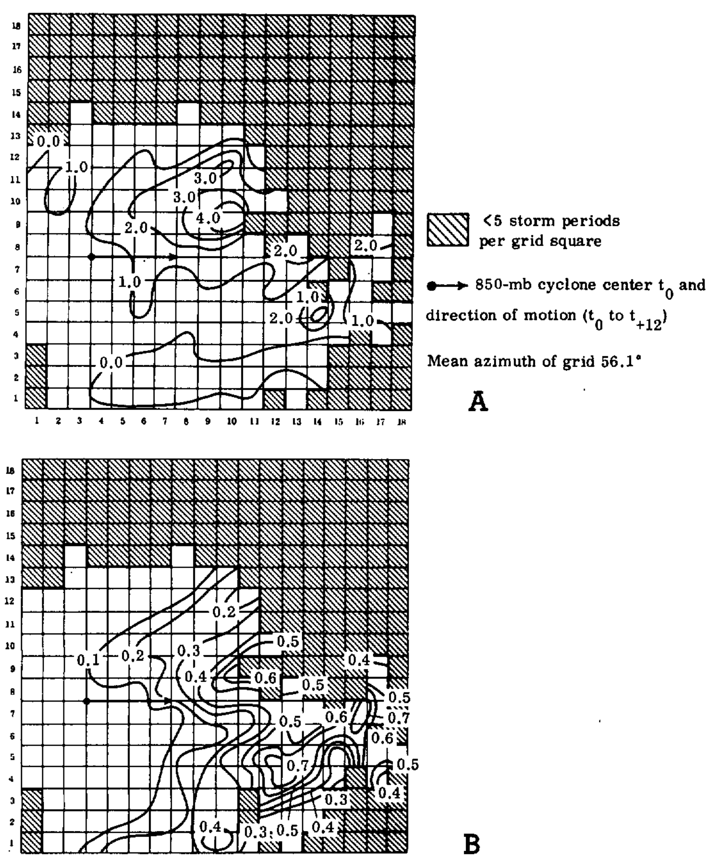


FIGURE 15.—Strong open waves and strong occlusions, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

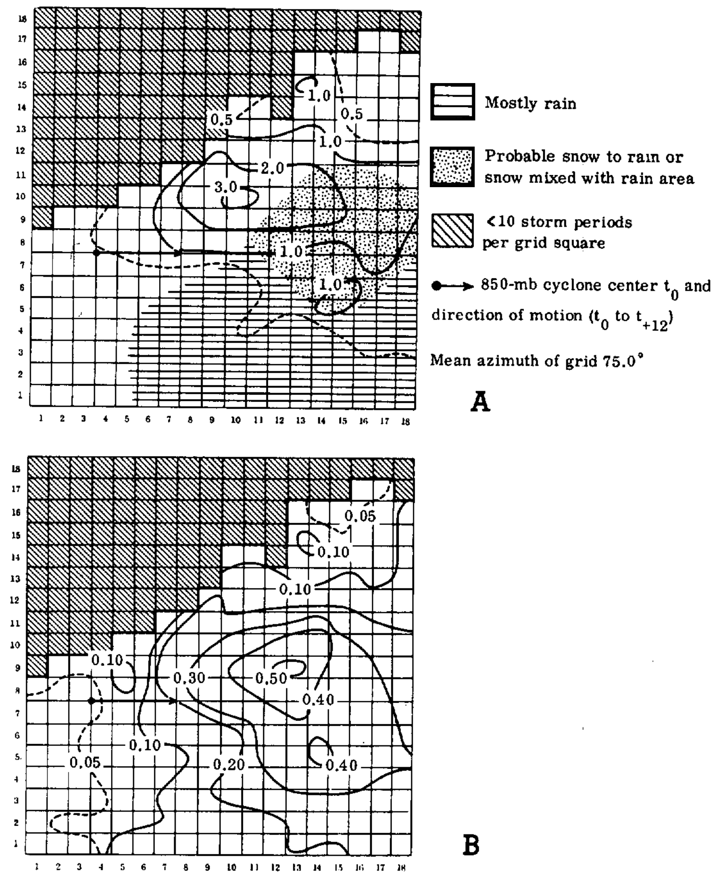


FIGURE 16.—Location of the cyclone center west of the Appalachians, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

B. STRATIFICATION OF CYCLONES BY INITIAL LOCATION

The Atlantic Ocean has an important influence on the character of East Coast snowfalls. Because we believed that snowfall and precipitation patterns and amounts associated with cyclones that are initially located east of the Appalachians may differ from those of cyclones initially located west o the Appalachians, the snowfall and precipitation data were stratified according to the initial location of the 850-mb cyclone.

Figures 16A and 16B show mean snowfall and mean precipitation for cyclones initially west of the Appalachians. The interesting information in these figures may be summarized as follows:

1. For cyclones initially west of the Appalachians rather substantial 12-hr mean melted precipitation amounts are noted both to the left and right of the direction of motion and well ahead of the cyclone, but mean snowfall amounts over a large portion of the grid are considerably less than the amounts that would be expected if the normal 10:1 ratio of snow amount to melted precipitation amount is applied. This strongly suggests that the dotted area in figure 16A often experiences snow changing to rain or snow that becomes mixed with rain, and that the hatched area experiences mostly rain.

2. For cyclones initially east of the Appalachians (figs. 17A and 17B), mean melted precipitation amounts and snowfall amounts show a very close correspondence to the normal 10:1 ratio of snow to melted precipitation, in the area to the left of the direction of motion of the 850-mb cyclone.

3. Significant mean snowfall amounts (>2 in., fig. 17A) begin about 300 mi ahead of the 850-mb cyclone and extend in a band

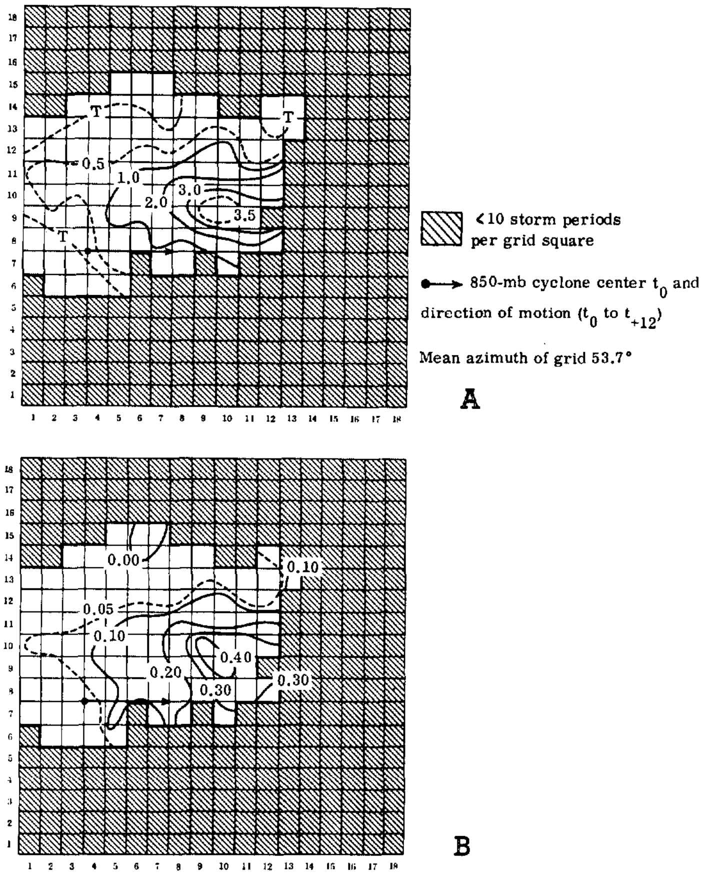


FIGURE 17.—Location of the cyclone center east of the Appalachians, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

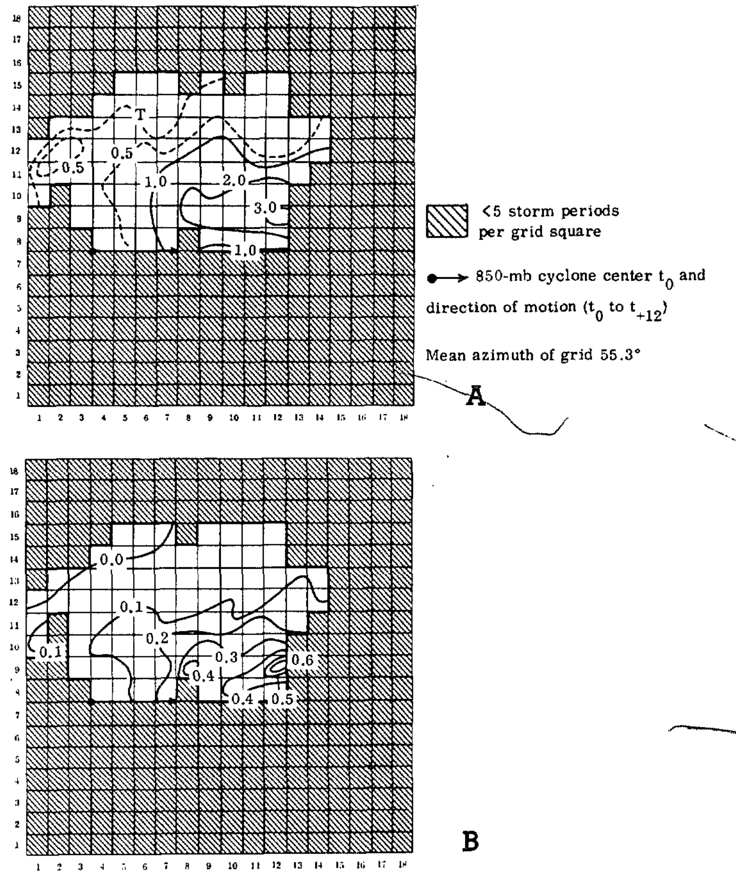


FIGURE 18.—Location of the cyclone center east of the Appalachians and south of 36°N, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

about 200 mi wide, out to at least 650 mi from the cyclone center. Insufficient data precluded a reliable analysis beyond this point.

Those cyclones initially east of the Appalachians are normally (although not exclusively) in the developmental stages when south of approximate latitude 36°N and are generally well-developed cyclones when they reach a point north of 36°N. Therefore, the cyclones east of the Appalachians were stratified again, into those first located south of latitude 36°N and those north of 36°N. There are easily recognizable differences between snow and precipitation amounts for these two stratifications, as shown in figures 18 and 19.

While a significant band of mean snowfall exists to the left of the axis of motion of the 850-mb cyclones that are initially south of 36°N, the amounts of mean melted precipitation over this band suggest that the water content of the snow is high; that is, the snow-to-rain ratio is about 5:1. For cyclones initially north of 36°N, *mean* maximum snowfall amounts in the time period t_{+6} to t_{+18} are from 4–6 in. in an area beginning about 300 mi ahead of the cyclone and extending in a band 70 to 200 mi to the left of the direction of motion, out to about 500 mi ahead of the cyclone. Significant snowfall amounts (>2 in.) cover a wide area 400 mi ahead of the cyclone, extending from the axis of the direction of motion to 350 mi to the left. Snow-to-melted-precipitation ratios are of the order of 10:1 or somewhat higher.

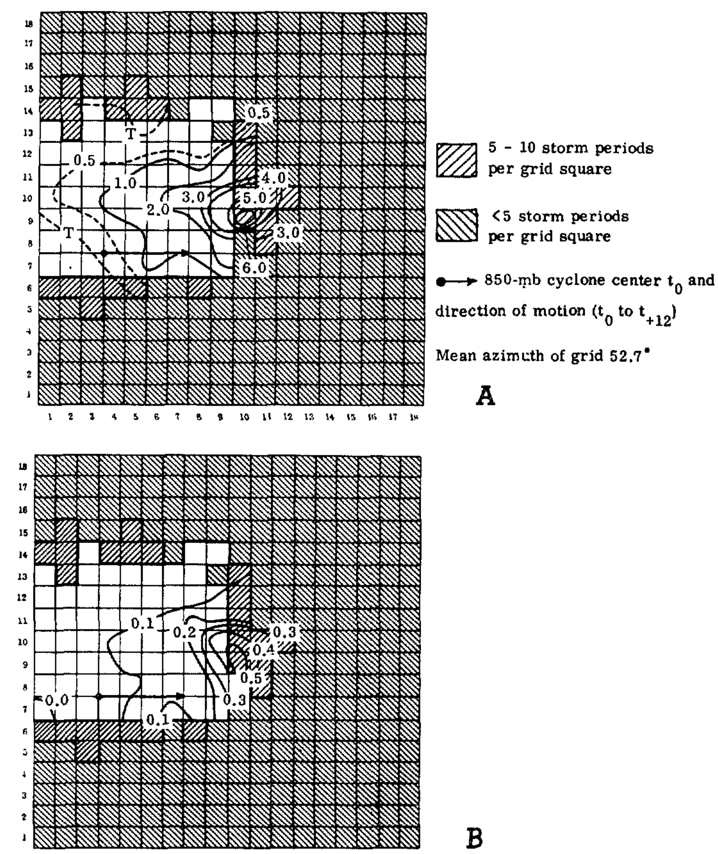


FIGURE 19.—Location of the cyclone center east of the Appalachians and north of 36°N, (A) mean snowfall, t_{+6} to t_{+18}, and (B) mean melted precipitation, t_{+6} to t_{+18}; units, inches.

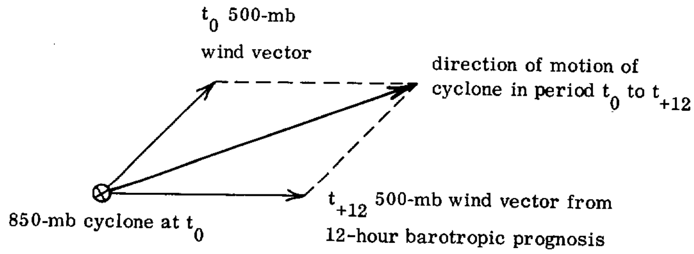


FIGURE 20.—Schematic representation of the procedure for determining the direction of motion of the 850-mb cyclone for grid orientation in an operational environment.

5. OPERATIONAL APPLICATION OF SNOWFALL AND PRECIPITATION FIELDS FOR PRECIPITATION

In an operational environment, the procedure for utilizing the snowfall and melted precipitation amounts and distributions in a predictive sense is fairly simple as follows:

1. Determine the location of the 850-mb cyclone at t_0 (analysis time).
2. Determine the resultant wind vector at 500 mb over the t_0 position of the 850-mb cyclone by adding the 500-mb wind vector at time t_0 to the wind vector at time t_{+12}, taken from the 12-hr 500-mb barotropic prognosis. Figure 20 depicts these first two steps.
3. Select the synoptic climatological grids appropriate to the current intensity and/or location of the 850-mb cyclone. For probabilities of precipitation, select the frequency grids and (for general application) the "all cyclone" mean snowfall and melted precipitation grids. (It will be necessary to construct grid overlays that coincide with the scale of the map being used.)
4. Place the origin of the grid(s) over the t_0 position of the 850-mb cyclone and orient the axis from the origin along the line given by the vector obtained in step (2).
5. Read off the mean snowfall, mean melted precipitation, and "precipitation probability" for areas of interest along the Atlantic Seaboard.

Two instances were found in which the general procedure described could not be applied, that is, cases in which the mean 500-mb vector could not be constructed by the steps outlined. These two cases and the recommended methods for obtaining the direction of motion of the grid for each case are as follows:

1. The 850-mb cyclone is vertical with the 500-mb cyclone or at the base of the 500-mb trough at initial time t_0.

Construct the vector for obtaining the direction of the 850-mb cyclone by the t_0 position and the position of the 500-mb closed Low (or base of trough) at t_{+12}. See figures 21A and 21B.

2. The 850-mb cyclone at t_0 is ahead of the t_0 500-mb trough but is positioned at the base of the t_{+12} location of the 500-mb trough, that is, in the region of sharpest curvature so that the direction of the t_{+12} 500-mb vector wind is in doubt. Since the 850-mb cyclone is ahead of the 500-mb trough most of the period between t_0 and t_{+12}, orient the grid from the t_0 position of the 850-mb cyclone and the t_0 500-mb geostrophic wind vector and then *adjust the direction of motion 10° in a clockwise direction,* as shown in figure 22.

The fields of snowfall and melted precipitation relative to the 850-mb cyclone are based on an average forward speed of about 30 mi/hr for all cyclones during the period of the data sample (speed-of-cyclone ranges for various categories was within rather narrow limits, 27 to 34 mi/hr). In operational application of these fields, adjustment is necessary for expected cyclone speeds ≥ 5 mi/hr slower or faster than 30 mi/hr. Our recommendation for adjusting

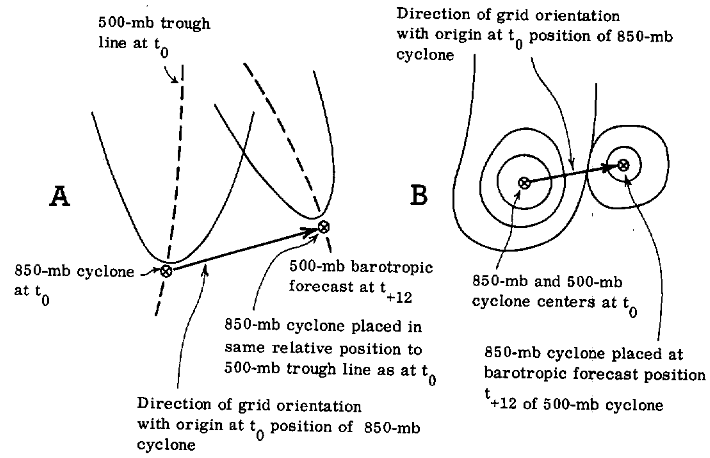


FIGURE 21.—Grid orientation when the 850-mb cyclone is (A) vertical with the base of the 500-mb trough at t_0 and (B) vertical with the 500-mb cyclone at t_0.

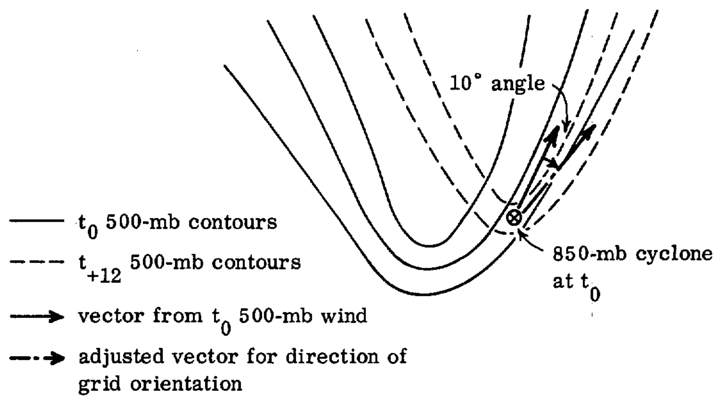


FIGURE 22.—Grid orientation when the 850-mb cyclone is vertical with the base of the trough at the t_{+12} 500-mb trough position.

the grids is to move the origin back along the axis of direction of motion by one grid square for every 5 mi/hr that the expected rate of forward motion of the cyclone is less than 30 mi/hr and forward by one grid square for every 5 mi/hr that the expected rate is over 30 mi/hr.

The expected rate of speed of the 850-mb cyclone may be approximated by computing an average of the t_0 and t_{+12} 500-mb geostrophic wind speeds over the t_0 position of the cyclone, then taking 50 percent of the average 500-mb geostrophic winds.

When the 850-mb cyclone at t_0 is vertical with a 500-mb trough or with a 500-mb closed Low, the assumption is that it will remain vertical with the 500-mb trough or Low for 12 hr. Thus, the expected rate of speed of the 850-mb cyclone in these instances is given by the 500-mb 12-hr barotropic prognosis of the trough or cyclone.

With the recommended procedures for obtaining the grid orientation and any necessary adjustments in an operational environment, the synoptic climatologies of snowfall and precipitation may be applied in any situation.

There are other techniques available for determining the 12-hr prediction of location of the 850-mb cyclone (among them, predictions from the PE, primative equation, model). Any of them may be used to orient the grid and apply the synoptic climatologies.

Because the climatologies represent *averages*, caution must be exercised in applying them in an operational framework as individual cases may vary significantly from the average. These averages, though, are valuable in determining precipitation probabilities and in determining areas in which the potential for moderate to heavy snow normally exists (in the period from time t_{+6} to t_{+18}). Adjustments that are necessary for individual cases include considering the moisture, temperature, vorticity, and the vertical motion fields, topography, and the distance of the area of interest from the coast.

6. TEST OF PREDICTION METHOD

A. GRID ORIENTATION PROCEDURE FOR 1968–1969 CYCLONES

The procedure for orienting the snowfall and precipitation grids was tested on 21 cyclones at the 850-mb level for the winter season 1968–1969. In the great majority of cases, the procedure gives an excellent approximation of the direction of the cyclone. Average error for the 73 12-hr time periods associated with the 21 cyclones was only 8°; the root-mean-square (rms) error was 9.7° (figs. included in Spiegler and Fisher 1970).

B. APPLICATION OF "PROGNOSTIC" FIELDS TO SELECTED 1968–1969 SNOWSTORMS

A qualitative investigation was made to determine how the snowfall and precipitation model and synoptic climatologies performed on four randomly selected [3] East Coast snowstorms (comprising 11, 12-hr "forecast periods") from the 1968–1969 season. (The 1968–1969 snowfall data were not used in the development of the synoptic climatologies.) Only four storms were assessed because of limited data. The four storms selected occurred on February 9–10, February 16–17, March 1–4, and March 9–10 (all in 1969). Observed precipitation patterns for these dates were taken from surface charts. A discussion of these storms follows. The grids were oriented according to the procedure described in section 5. Throughout the discussion, the terms "prognostic fields" and "synoptic climatologies" are interchangeable.

Cyclone of February 9–10, 1969. This storm was one of a series of East Coast snowstorms that affected the Northeastern States in February and early March 1969. The first forecast period is based on the 0000 GMT February 9 850-mb chart and is for the 12-hr period from 0600 to 1800 GMT on February 9.

The grid orientation procedure gave a resultant motion of the 850-mb cyclone somewhat to the south of east, toward the mid-Atlantic coast. The direction error for the previous 12-hr period was small, approximately 10° to the right of the actual direction; and examination of the errors for all cyclones for the 1968–1969 winter revealed that the errors do not normally increase with time (through the history of any cyclone). Thus, one can have confidence in the forecast direction of motion when the initial forecast error is near or less than the overall rms error of 9.7°. Because the 850-mb charts are 12 hr apart, the sequence of events that resulted in an 850-mb cyclone just off the mid-Atlantic coast at 1200 GMT on February 9, is open to some question. Translation of the 850-mb cyclone located in southwest Ohio at 0000 GMT on February 9, to off the mid-Atlantic coast at 1200 GMT on February 9 requires a forward speed of just under 50 mi/hr, which is inconsistent with both prior and subsequent forward speeds. The potential for secondary cyclone development at the surface was recognized during the afternoon of February 8 from reports of rapidly falling pressures over the Carolinas. It is quite possible that the secondary development, once underway, reflected upward to the 850-mb level by 1200 GMT on February 9. In any case, the resultant error of the direction of motion was small. Spar et al. (1969) evaluated local numerical forecasts from the viewpoint of local snow prediction for the 1967–1968 and 1968–1969 winters based on the PE model. In their study, there is a thorough description of the history of the storm of February 9–10 and the forecasts given by the PE model, as well as the subjective forecasts issued by the Weather Bureau (now the National Weather Service, Washington, D.C.) based largely on input from the PE model. They report that the numerical prediction indicated a warming trend for the East Coast which was not observed, primarily because of "the failure of the numerical model to anticipate the secondary cyclogenesis."

An interesting qualitative comparison of the numerical prognoses (PE and barotropic) during the 7-week period from early February through mid-March 1969 showed the barotropic was superior in handling the small amplitude short wave troughs in the United States—the barotropic correctly retained their identity, while the PE model damped them out with time. These short waves played a very important role in the cyclogenesis process near the eastern seaboard that was a frequent occurrence during the 7-week period. It would be interesting to perform a diagnostic study to try to determine the reasons for the model's behavior during this period.

Related to the discussion of the cyclone of Feb. 9–10, 1969, the "forecasts" given by the snowfall grids are shown in figures 23A to 23C, and the observed patterns are shown in figures 24A to 24C. The cyclone was typed "moderate occlusion" at the time it was on the Ohio-Indiana border. The "moderate occlusion" synoptic climatology of mean snowfall shows a 6-in. maximum near New York City for the first 12-hr period. (The synoptic climatologies used are noted on each figure.) The observed precipitation pattern shown in figure 24A for the first forecast period is in good agreement with that given by applying appropriate synoptic climatology, except that the limit of measurable snow was observed to have advanced about 200 mi farther into New England by 1800 GMT.

[3] The 850-mb cyclones were numbered 1 to 21, and slips of paper with these numbers were selected blindfoldly from among the total number.

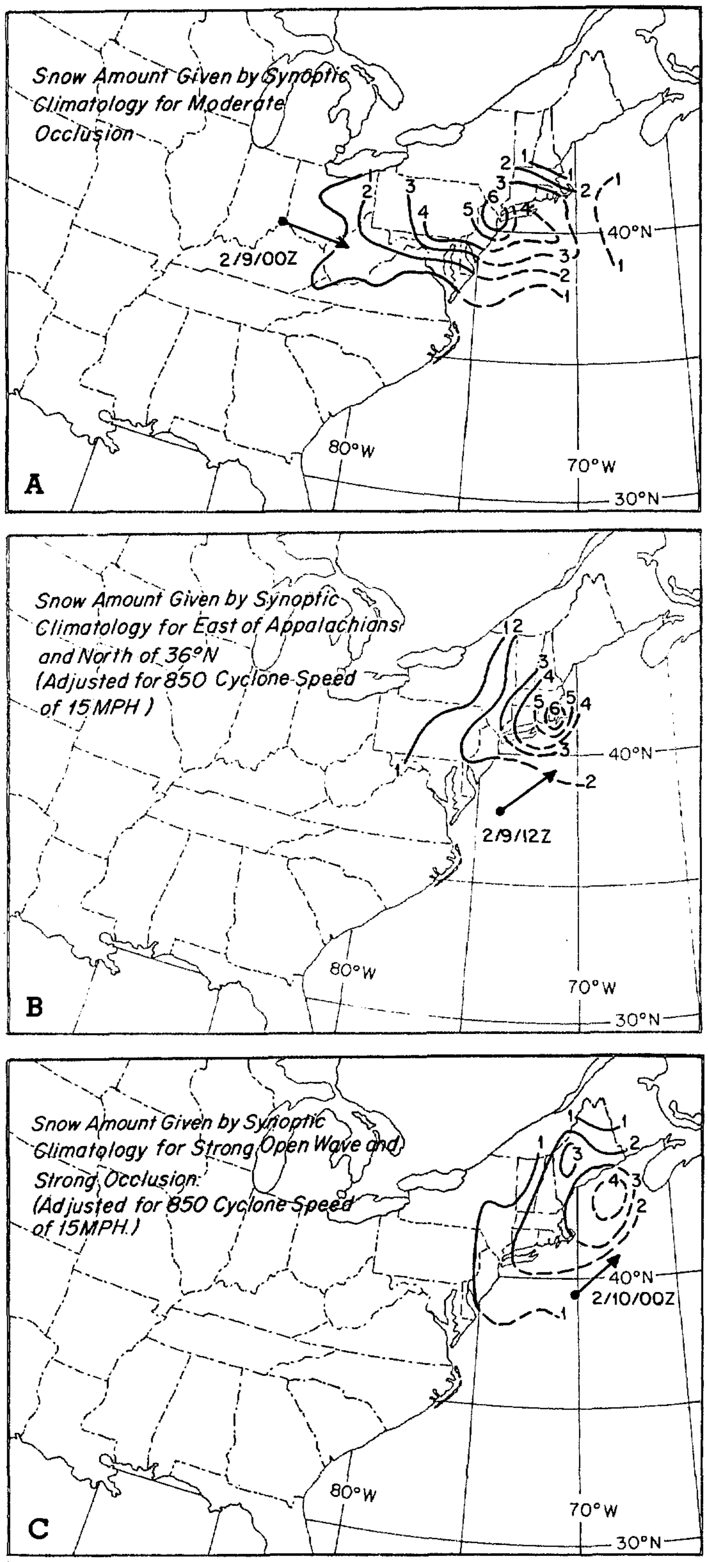


FIGURE 23.—Application of the snow-prediction model to the storm of Feb. 9–10, 1969; (A) 0000 GMT on February 9, (B) 1200 GMT on February 9, and (C) 0000 GMT on February 10; units, inches.

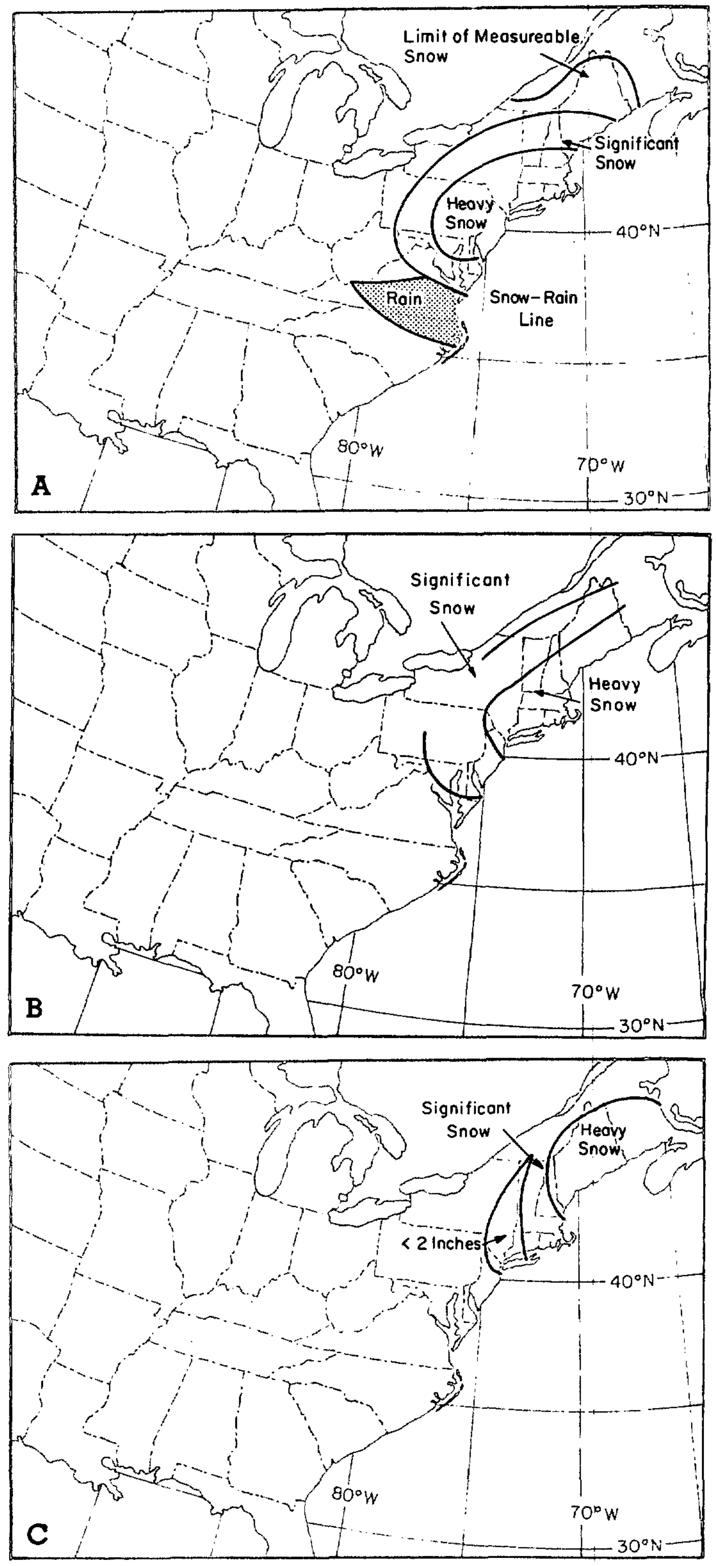


FIGURE 24.—Observed precipitation pattern for the storm of Feb. 9–10, 1969; (A) 0600 to 1800 GMT on February 9, (B) 1800 GMT on February 9 to 0600 GMT on February 10, and (C) 0600 to 1800 GMT on February 10.

The model also gave excellent results for the next two 12-hr forecast periods. For the 1200 GMT February 9 and 0000 GMT February 10 forecasts, there was a choice of synoptic climatologies for snow amount. For 1200 GMT, the "east of the Appalachians, north of 36°N" was used, but adjusted back 3° of latitude by the procedure discussed in section 5. By 0000 GMT, the 850-mb cyclone was a strong occlusion, and the synoptic climatology snow amount "forecast" is in good agreement with the observed pattern. Thus, for this particular storm, the derived prognostic fields provided very useful information.

Cyclones of February 16–17, March 1–4, and March 9–10. Details of the verifications for these three storms are given in Spiegler and Fisher (1970). In general, however, the "prognostic" fields provided useful guidance for these storms; and adjustments necessary to account for the particular synoptic patterns were not difficult to determine.

C. TEST OF PREDICTION METHOD FOR 1969–1970 SNOWSTORMS

The Scientific Services Division of the Eastern Region Headquarters, ESSA Weather Bureau, tested the suggested prediction procedures on some of the 1969–1970 winter cyclones. The report (Wasserman 1970) sent back to the authors indicated that the prediction method gave very good results for the storms on which it was tested. Also related was the fact that the application of the method required only 10 to 15 min. Because the barotropic 500-mb prognosis (necessary to the application) is transmitted by 1000 and 2200 EST, it is feasible to generate the snowfall and precipitation predictions in time for use as guidance in preparing the 1100 and 2300 regional forecasts.

7. SNOWFALLS ALONG THE ATLANTIC SEABOARD WITHOUT THE PRESENCE OF 850-MILLIBAR CYCLONES

In a study of the correlation between snowfall amounts and the presence of a cyclone at the 850-mb level, it is important to ask what is the situation *when there is no cyclone* at the 850-mb level, specifically:

What is the frequency of significant snowfalls—4 in. or more within 24 hr—on the synoptic scale? [4]

What are the typical atmospheric conditions leading to these snowfalls?

Frequency of significant snowfalls without 850-mb cyclones. From the Environmental Data Service (ESSA, now NOAA), Silver Spring, Md., *Climatological Data* books for the Atlantic Seaboard States, from South Carolina to Maine, for the eight winters (1960–1961 to 1967–1968) were used for a determination of the frequency of significant snow events that occurred when there was no 850-mb cyclone present.

Data were analyzed for four zones (fig. 25), and results for various categories of snowfall amount are shown in table 2. In about 70 percent of the cases in the total sample, an 850-mb cyclone developed *later* in the storm period. The important information here is as follows:

In zones 3 and 4, only one case (2% of the total cases in the respective zones) had snowfall in the 7- to 10-in. category; 9 percent were in the 4- to 6-in. category. Thus, the frequency of substantial snowfall on the synoptic scale, without the presence of an 850-mb cyclone, is 11 percent in these zones, from southern New Jersey and southern Pennsylvania to Maine.

[4] In the synoptic climatologies (sec. 4), "significant" snowfall was defined as >2 in. in 12 hr.

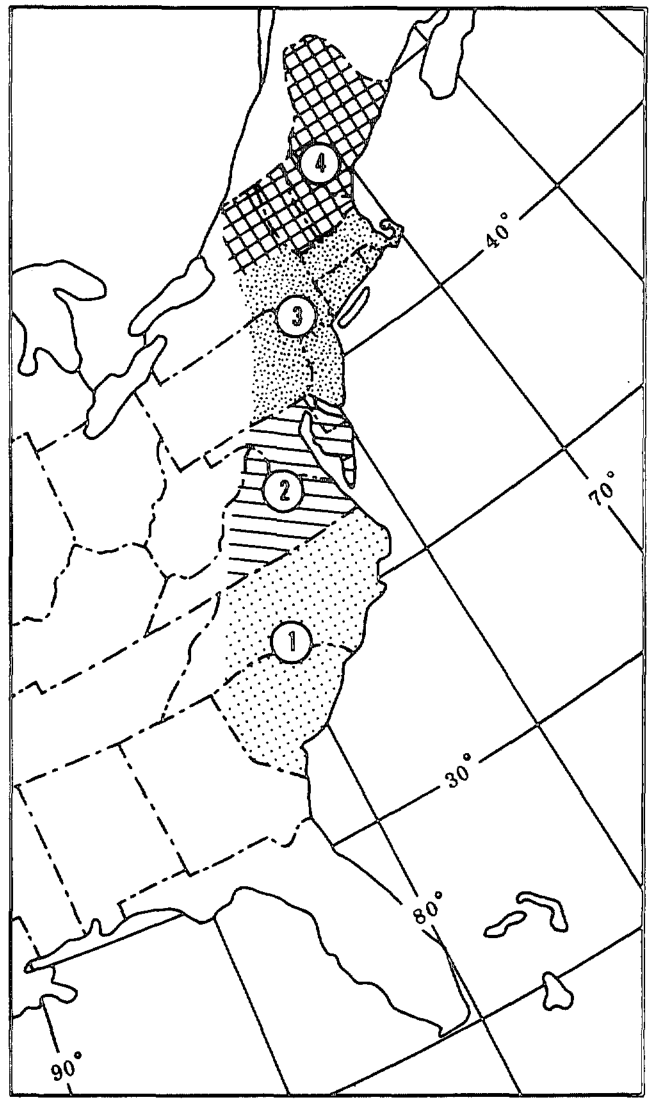


FIGURE 25.—Zones defined in the snowfall prediction study.

TABLE 2.—*Frequency of snowfall within categories of snow amount (in inches) without the presence of the 850-mb cyclone*

Zone*	Total cases	Snow-amount categories				
		>10	7–10	4–6	1–3	<1
1	35	0	0	0	6	29
		0	0	0	17%	83%
2	48	0	0	7	3	38
		0	0	15%	6%	79%
3	53	0	1	5	14	33
		0	2%	9%	26%	63%
4	47	0	1	4	16	26
		0	2%	9%	34%	55%

*See figure 25.

For zone 2, comprising Virginia, Maryland, and Delaware, there were only seven snow events or 15 percent of the 48 cases in the 4- to 6-in. category and none in the higher categories.

For zone 1, the Carolinas, there were no cases of snowfall more than 3 in. on the synoptic scale in the absence of an 850-mb cyclone.

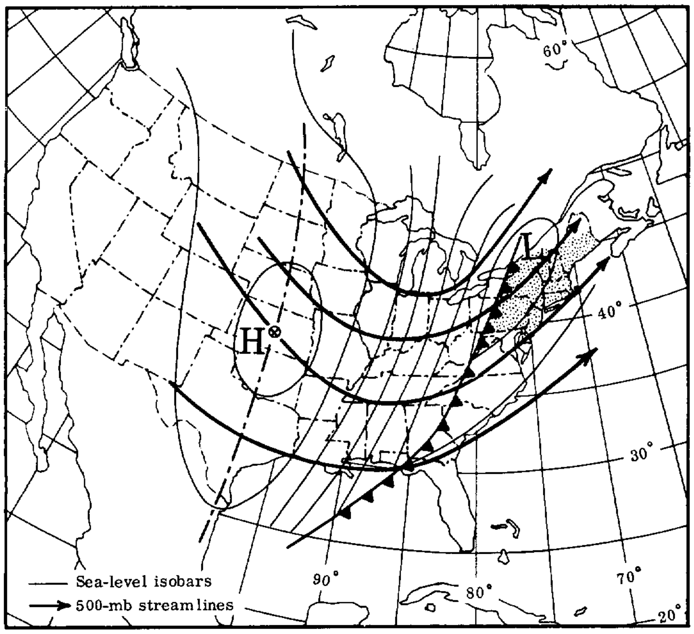


FIGURE 26.—Type 1 synoptic weather pattern that may lead to significant snowfalls without the presence of 850-mb cyclones.

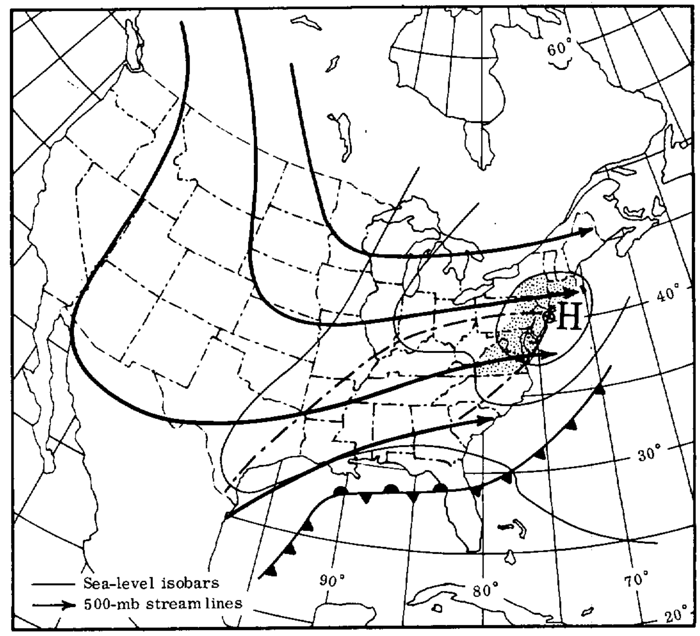


FIGURE 27.—Type 2 synoptic weather pattern that may lead to significant snowfalls without the presence of 850-mb cyclones.

If all synoptic scale snow events in the eight winters' total sample are considered, the frequency of significant snow ($\geq$4 in.) without associated 850-mb cyclones is less than 5 percent.

Aside from the low number of snowfalls in the 4- to 10-in. range when there is no 850-mb cyclone present, it is interesting that, in this sample, there were *no* snowfalls of more than 10 in. in the absence of an 850-mb cyclone.

Atmospheric conditions prior to significant snowfalls in the absence of an 850-mb cyclone. Despite the relatively low frequency of significant snow events without 850-mb cyclones, an investigation was made into the synoptic conditions preceding those that did occur during the eight winters of our sample. Sea-level and 500-mb charts were examined; three types of synoptic conditions showed up repeatedly. These are shown in figures 26 to 28.

Type 1 conditions (fig. 26) affect zones 3 and 4 and are characterized, at the surface, by a cold front (or occluded front) that extends from central or western New York State to the east Gulf States and by a high-pressure ridge with a north-south axis through central United States. The air flow behind the cold front is generally from a northerly direction (as opposed to a northwesterly direction), and there is steady snowfall behind the front. The composite 500-mb pattern shows a rather broad trough through the Great Lakes region and southwest winds along the Atlantic Seaboard. Snowfalls in zone 4 (northern New England) may easily be 4 to 6 in. with somewhat lower amounts over zone 3. Usually, an 850-mb cyclone forms, but forms too late for use in the prediction of snowfall.

Type 2 conditions (fig. 27) show a surface High somewhere between New England and the Middle Atlantic States, with a ridge along the Atlantic Seaboard and a stationary or warm front in the northern Gulf of Mexico, extending east-northeastward off the south Atlantic coast. At the 500-mb level, the main feature is a broad trough in the central United States and confluent flow with west-to-southwest winds causing overrunning precipitation over the South Atlantic and Middle Atlantic States. The northern limit of the confluence zone usually coincides with the limit of significant snowfall and, in many cases, it is near the border between zones 2 and 3.

Type 3 conditions (fig. 28) primarily affect zones 2 and 3 with snowfall (zone 1 often receives a rain-snow mixture). The main feature is a massive Arctic outbreak, the leading edge of which passes off the east coast at sea level and becomes a slow-moving cold front with stable waves located off the south Atlantic coast. In the midtroposphere, the polar jet stream is usually far to the south over the Gulf States; and a stationary broad trough is evident over the eastern two-thirds of the United States causing west-to-southwest winds over the South Atlantic and Middle Atlantic States. This creates an "overrunning" type of precipitation over this area. Because the midtropospheric trough is broad and stationary, the waves on the polar front usually remain stable. Any sharpening and eastward movement of the trough, toward the low-level baroclinic zone off the coast, will immediately lead to cyclogenesis on the front. In the winters of our data sample, this only occurred once. Most of the type 3 conditions in the cases we studied had only minor perturbations moving through the broad trough.

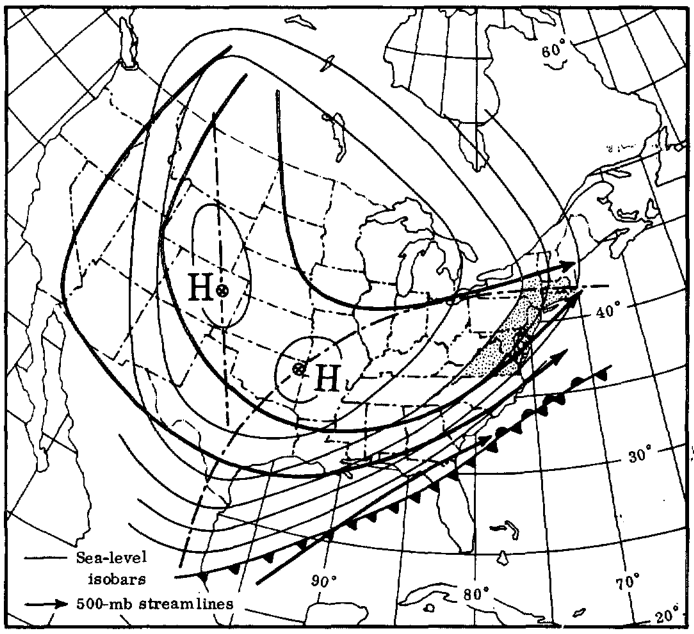


FIGURE 28.—Type 3 synoptic weather pattern that may lead to significant snowfalls without the presence of 850-mb cyclones.

Significant snows on the synoptic scale in the absence of 850-mb cyclones also occurred under other conditions, particularly in zones 3 and 4; but these were isolated single occurrences: classification into a "type" was not warranted. We did not investigate the total number of times that these three most prominent types of conditions prevailed, without regard to whether significant snowfalls occurred. Thus, we cannot say how often these three types of atmospheric conditions lead to significant snowfalls in areas along the Atlantic Seaboard—but we can say that the potential for significant snowfalls should be recognized when one of these types occurs in the absence of an 850-mb cyclone.

8. CONCLUSIONS AND RECOMMENDATIONS

The study resulted in two useful products:

1. An objective prediction method for snowfall and melted precipitation associated with 850-mb cyclones along the Atlantic Seaboard that was shown to provide useful guidance in an operational forecast environment.
2. A determination of the frequency of significant snow events on the synoptic scales ($\geq$4 in. in 24 hr) for regions along the Atlantic Seaboard not associated with the presence of an 850-mb cyclone. The synoptic conditions leading to most of these snow events were also identified.

Although the application of the synoptic climatologies of snowfall and melted precipitation as prognostic fields gave very useful guidance for storms during the 1968–1969 and 1969–1970 winters, it should be stressed that, as with most atmospheric prediction models, they are not intended to be applied and accepted strictly in all situations. In many instances, it is not difficult to foretell over which areas the "forecasts" given by the climatologies may *not* verify well; adjustments or improvements may then be made based on the general moisture and temperature conditions, and the circulation pattern, over the region of interest. It would be desirable to improve the synoptic climatologies by *objectively* taking into account those items just mentioned. This may be accomplished by deriving regression-type prediction equations for each grid square based on a series of experiments that utilize upper air temperature, moisture, wind and vorticity (initial and numerically forecast) parameters as possible predictors.

Because there is a completely different situation, in a physical sense, between the occurrence of rain (or snow) and the nonoccurrence of snow, it is necessary to discriminate between the "no-snow" and the "rain" cases over areas of the grid. Therefore, it is recommended that three sets of prediction equations be derived for grid squares: (1) precipitation-no precipitation, (2) precipitation type, and (3) snowfall amount (for snow cases only).

It appears logical that the predictions from synoptic-climatological snowfall distributions around 850-mb cyclones can be sharpened by the addition of upper air information in a quantitative consistent manner.

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